FINAL REPORT NW CSC-FUNDED PROJECT

1. ADMINISTRATIVE:

Project Title: **Rangewide climate vulnerability assessment for threatened Bull Trout**

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[1] Includes $200,000 from the NW CSC and $50,000 from U.S. Fish and Wildlife Service

2. PUBLIC SUMMARY:

Bull Trout is the most cold-adapted fish in freshwaters of the Pacific Northwest. The species is listed as threatened under the U.S. Endangered Species Act, but climate warming may place the species at further risk. Climate warming may lead to warming of streams in summer and increasing probability of floods in winter, leading to widespread loss of habitat projected for Bull Trout. This project seeks to further elaborate how these climate-related threats influence Bull Trout across five western states (OR, WA, ID, MT, NV). These states form the southern margin of the species' range. We used predictions of temperatures in streams across approximately two-thirds of this extent to map coldwater streams or "patches" suitable for spawning and early rearing of Bull Trout. Our results indicate that larger patches of cold water were much more likely to support the species. We also found that Bull Trout were more likely present in patches with extremely cold (<10C or 50F) temperatures in summer (August), fewer floods in winter, and low human influences as measured by the Human Footprint index. In addition to elucidating the importance of local and climate-related threats, our work has identified dozens of places where Bull Trout may exist, but have not yet been detected, as well as other places where Bull Trout have been observed recently, but may be at high risk of local extinction. Future work will focus on completing these analyses across the range of Bull Trout in the conterminous United States.

3. TECHNICAL SUMMARY:

Bull Trout is the most cold-adapted fish in freshwaters of the Pacific Northwest. The species is listed as threatened under the U.S. Endangered Species Act, but climate warming may place the species at further risk. This project seeks to further elaborate how these climate-related threats influence Bull Trout across five western states (OR, WA, ID, MT, NV). These states form the southern margin of the species' range. We used predictions of temperatures in streams across approximately two-thirds of this extent to map coldwater streams or "patches" suitable for spawning and early rearing of Bull Trout. We also derived a suite of covariates related to climatic or local factors hypothesized to influence Bull Trout and modeled their relationship to species' presence across the study domain. Within a subset of the data, we evaluated the potential bias in our model estimates related to imperfect detection of Bull Trout. Overall, we did not find evidence for substantial bias in our approach that is attributable to imperfect detection, although it is clear that dozens of locations that may support Bull Trout remain to be completely surveyed. Across the domain that we considered, four factors were most important in relation to presence of Bull Trout: size of stream networks supporting cold water suitable for spawning and early rearing of Bull Trout, the presence of very cold water within these networks, absence of winter high flows, and low level of human disturbance. Three of these covariates are very strongly sensitive to climate change (size of stream networks, cold water, winter flooding), reflecting the sensitivity of Bull Trout to climate change. With the exception of very cold water, all of these covariates showed strong spatial variation in their relationships with the presence of Bull Trout. This indicates that many threats may be location-specific. To date, we have published two articles in peer reviewed journals related to this work and plan a final publication to be readied by 2015 as key information for this project becomes available across the range of Bull Trout in the conterminous United States. Although results in hand do not yet represent the complete range of the species, existing results and products have already been put into practice in several locations and show great promise for evaluating the status of the species and threats operating at broad extents.

4. PURPOSE AND OBJECTIVES:

Bull Trout (*Salvelinus confluentus*) is one of the most cold-adapted species in freshwater in North America (Selong et al. 2001; Dunham et al. 2003). The species is listed as threatened under the U.S. Endangered Species Act throughout its range within the conterminous United States (USFWS 2002, 2008), which encompasses a vast geography, including major river systems such as the Klamath and Columbia Rivers, and a host of Pacific coastal rivers in Washington State, as well as river systems originating east of the continental divide in northern Montana and ultimately draining to the Atlantic Ocean. The conterminous United States represents southern extent of the range of Bull Trout, where local populations are restricted to small enclaves representing the coldest portions of river networks, lakes, and, more recently, human-constructed reservoirs.

The naturally fragmented distribution of Bull Trout has been further dissected by impassible dams, diversions, degraded water quality, and invasive species (Rieman et al. 1997; Dunham et al. 2008). Whereas the status of populations of Bull Trout across the species range is highly variable, these historical and contemporary threats are a major reason for why Bull Trout continues to require formal protections (USFWS, 2008). Recent analyses characterizing future threats to Bull Trout posed by climate change have prompted additional concern (e.g., Rieman et al. 2007; Isaak et al. 2010a; Wenger et al. 2011).

Our fundamental objective in this project is to evaluate climate-related and local threats to Bull Trout and to provide an objective and unified framework for evaluating them together across the species' range within the conterminous United States. To this end, we have 1) developed and applied methods for delineating and mapping discrete patches of habitat that support spawning and early rearing of Bull Trout, 2) attributed these patches with covariates indicating climate-related and local threats to Bull Trout, and 3) developed models to relate these covariates to presence of Bull Trout to identify the most important factors influencing presence, and to quantify spatial variation in their influences. With these models and predictions in hand, we show how they can be applied to evaluate status and threats to Bull Trout.

5. ORGANIZATION AND APPROACH:

Task 1. Defining the units of study: patch delineation

Rationale

Before delving into the details of various factors influencing Bull Trout, it is critical to begin with a consideration of scale (Dunham et al. 2002; Peterson and Dunham 2010). In the simplest terms, scale refers to the spatial (or temporal) dimensions of a study, including the grain or resolution of the study and the extent. In stream fish ecology, the spatial grain of a study is often represented by a fixed length of stream (e.g., sampling sites) or units linked to geomorphic delineations, such as habitat units (pools, runs, riffles) or stream reaches (Frissell et al. 1986). Spatial extent is the area over which study units are distributed and assumed to represent. A common study approach involves sites (grain) distributed within a stream catchment or larger area (extent). Some examples linked to Bull Trout are summarized herein (Table 1).

An important issue linked to scale is that key processes can change across scales, and that constraints at larger scales may operate to control patterns at finer scales. For example, native and nonnative species may appear to co-occur in larger grains, but at a higher resolution or finer grain, segregation of species is more obvious (Melbourne et al. 2006). This pattern is evident in the case of Bull Trout, where lack of an influence of nonnative Brook Trout on presence of Bull Trout in headwater catchments is contrasted against patterns of segregation at sites within individual streams (Dunham and Rieman 1999; Rieman et al. 2006). The main process determining presence of Bull Trout in headwater stream catchments (or patches; Table 1) is persistence tied to their size and connectivity, with little influence of nonnative Brook Trout (Dunham and Rieman 1999). At a finer resolution in the same system, thermal gradients and interactive segregation among Brook and Bull Trout within streams is evident (Rieman et al. 2006). These contrasting results are not in conflict, they simply reflect the importance of different processes operating at different scales.

Given the pervasive influence of scale on our view of threats to Bull Trout, what is the appropriate scale for a rangewide vulnerability analysis? It has been argued that across broad extents, a "patch-based" perspective is the most appropriate for Bull Trout (Dunham et al. 2002). This is because patch geometry (size and connectivity) has an overarching influence on Bull Trout presence across broad landscapes. Patches for Bull Trout are defined by the presence of suitably cold temperatures (Dunham et al. 2003), which are typically restricted to the upstream-most headwaters of catchments. Accordingly, from a Bull Trout perspective, drainage networks consist of cold patches in headwaters connected by warmer streams where seasonal movements can allow for connectivity among patches and to migratory destinations (Figure 1). An important point about a patch-based perspective is the opportunity to identify suitable, but unoccupied, habitats based on probabilistic models of Bull Trout presence. Such information can prove invaluable for guiding recovery implementation (e.g., Dunham et al. 2011).

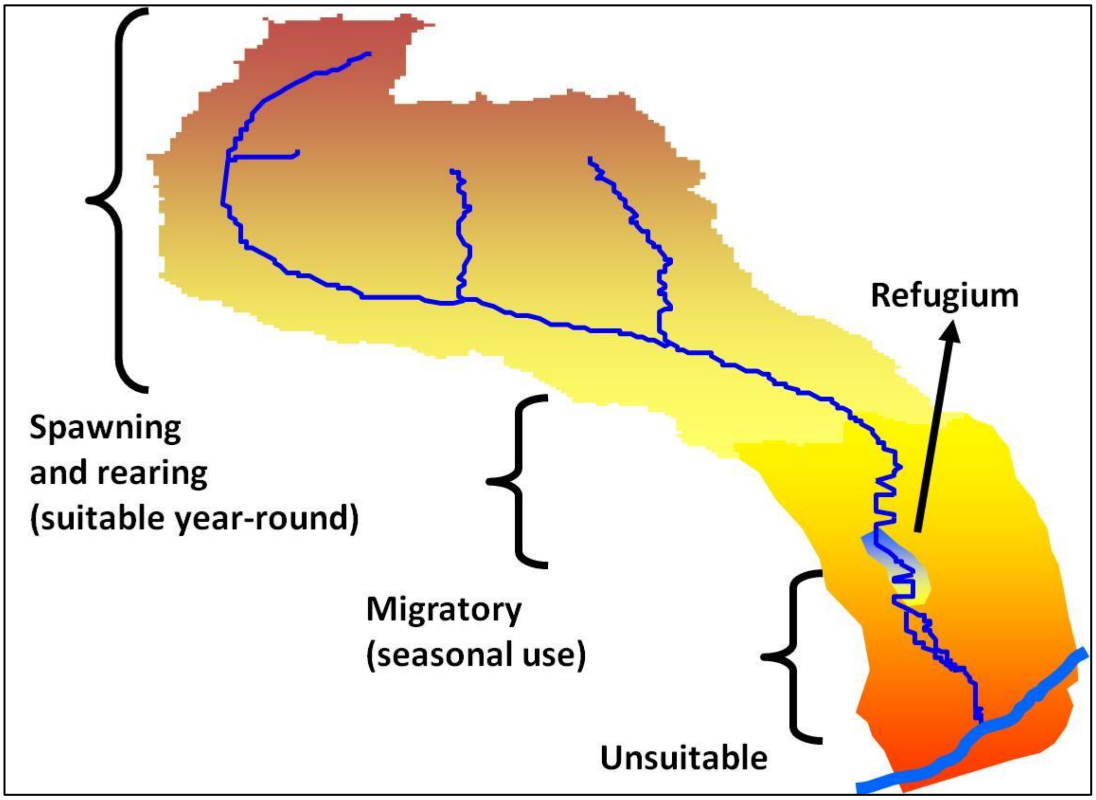
It is also possible to study Bull Trout at a finer grain (e.g., sites; Dunham et al. 2003; Wenger et al. 2011; Table 1), but presence at sites is constrained by patch geometry. In other words, suitable conditions at a site are necessary, but not sufficient, to support Bull Trout. If the larger patch, within which a site is embedded, is not large enough or connected enough to sustain a local population of Bull Trout, then individuals are unlikely to be present.

Because the finest unit of conservation for Bull Trout is a local population, which roughly corresponds to presence in a suitable patch of habitat (Table 1), a "patch" is the fundamental grain of this analysis. Patches can be aggregated into patch networks that approximate what are currently designated as core areas for Bull Trout, which can further be aggregated to consider major Distinct Population Segments, and ultimately the species' range within the conterminous United States.

Table 1. Associations between scale and recovery plan units for Bull Trout, with potential indicators of conditions for each (Peterson and Dunham 2011).

Scale	Recovery plan unit	Potential indicators
Site	**Not applicable**	**Temperature, channel features, etc.**
Patch	**Local population**	**Size, connectivity, distribution of conditions within a patch**
Patch network	**Core area**	**Number of patches, overall distribution of connectivity, distribution of conditions among patches**
Subbasin	**Recovery unit**	**Number and condition of patch networks within a DPS**
Region	**DPS**	**Number and condition of recovery units**

Figure 1. Illustration of a thermal landscape for Bull Trout, with perennially cold headwaters indicated for spawning and early rearing (Dunham et al. 2003), seasonal migratory corridors (may be too warm to support Bull Trout during portions of the year; Howell et al. 2010), cold thermal refuges, and unsuitable habitats, most often located in the downstream-most portions of stream networks.



Methods

Patches on a landscape represent discrete locations that provide conditions suitable to support a life stage or entire life cycle of a species (Dunham et al. 2002). In the case of Bull Trout, patches represent interconnected networks of streams with temperatures cold enough on a year-round basis to support spawning and early rearing. Determination of suitable thermal conditions is based largely on physiological and growth responses to temperature determined through laboratory experiments (Selong et al. 2001; Mesa et al. 2013) and associations between Bull Trout and temperature observed in broad-scale field studies (Dunham et al. 2003). Although Bull Trout can move widely outside of patches to utilize other habitats within or outside of stream networks on a seasonal or annual basis, patches represent the fundamental unit of the landscape that drive persistence of local populations (Dunham et al. 2002).

Patch delineation was based on medium resolution National Hydrography Dataset (NHD; http://nhd.usgs.gov/) streams with modeled temperatures available at 1km intervals, as provided by the NorWeST project (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). The NorWeST effort provides information on contemporary patterns of stream temperature that result from a combination of natural and human influences. With these data in hand, we run an ArcGIS ModelBuilder model (Environmental Systems Research Institute, Redlands, CA[2]) that automatically delineates patches in streams based on contiguous reaches of cold water. This process takes several steps, outlined in order below.

First, streams are filtered to remove reaches with an estimated mean summer streamflow of ≤0.034 $m^3.s^{-1}$ (estimated using data from Wenger et al. 2010), which corresponds approximately to streams with widths unlikely to be used by Bull Trout (<2m), based on Dunham and Rieman (1999; see also Peterson et al. 2012). The purpose of this step is to remove patches with only very small headwater streams that are unlikely to support Bull Trout. Without this step literally hundreds of very tiny patches can be generated within a given subbasin (eight digit hydrologic unit code; Seaber et al. 1987).

After the stream flow filter was applied, remaining stream reaches were coded on the basis of their August mean temperature, predicted by the NorWeST effort. Stream reaches with predicted temperatures of 13^{o}C or less were considered suitable, and coded as such. This temperature is near that for which maximum growth of Bull Trout fed on unlimited rations in laboratory conditions is observed, and far below temperatures at which Bull Trout begin to show signs of stress (Selong et al. 2001). In some cases, contiguous stream reaches that exceeded 13^{o}C were bounded on up- and downstream ends by reaches with predicted temperatures of 13^{o}C or less. Accordingly, we needed a set of rules for determining whether to subsume these reaches into a patch or not based on 1) the magnitude to which temperatures in such reaches exceeded 13^{o}C, and 2) the distance over which such exceedances were observed. If the temperatures in a given reach bracketed by suitably cold reaches did not exceed 14.75 ^{o}C, and the length of the reach was less than or equal to 4km, we included this reach as part of the larger network within which it was embedded. If this distance was more than 4km, the cold-water network was split by the warm patch. We coded stream reaches with predicted August mean temperatures greater than 14.75 ^{o}C to be unconditionally unsuitable (regardless of distance). This upper threshold translates into an approximate 5% decline in growth relative to the fastest rate of growth observed by Selong et al. (2001).

Lakes and dams are special cases, and can override the temperature coding. If a reach or set of reaches that make up a lake intersects a suitable cold-water reach, those lake-coded reaches are recoded as suitable, regardless of the temperature of the lake. Wherever a dam lies within a stream reach, that reach is automatically coded as unsuitable, breaking any otherwise potentially suitable patch. We identified dams from the Army Corps of Engineers National Inventory of Dams (http://geo.usace.army.mil/pgis/f?p=397:1:0), which provides complete coverage for the range of Bull Trout, but does not cover the entire range of natural and human caused barriers that exist on the landscape (e.g., Januchowski-Hartley et al. 2013).

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[2] Maps throughout this manuscript were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com. Please note that use of trade or firm names in this document is for reader information only and does not constitute endorsement of any product or service by the U.S. Government.

Finally, after all stream reaches were coded, we grouped contiguous suitably-cold stream reaches into discrete “patches” and assigned each individual “patch” a unique identifier.

Task 2. Patch attribution

Rationale

Once patches were created, we sought to attribute them with information on characteristics hypothesized to influence presence of Bull Trout (Table 2, 3). We selected characteristics linked to fragmentation of spawning and rearing habitat (patch sizes and connectivity), migratory connectivity (or habitat complementation; Dunning et al. 1992), presence of nonnative Trout, measures of local human influences (an index of human disturbance and presence of barriers), and factors with strong linkages to climate, including stream temperature, discharge, and wildfire (Table 2, 3).

Table 2. Overview of major categories of covariates considered in relation to presence of Bull Trout in spawning and rearing patches. A description of each covariate is provided, along with abbreviations used (when needed) in the text narrative.

Category	**Covariate**	**Description**	**Abbreviation**
Patch size	Spawning and rearing patch size	Amount of suitable coldwater habitat available for spawning and early rearing, expressed in terms of stream network length	P_size
Connectivity	Spawning and rearing patch connectivity	Distance from a given spawning and rearing patch to other spawning and rearing patches	P_conn
Habitat complementation	Migratory habitat size and connectivity	Habitat size-weighted connectivity of patches to lakes and reservoirs designated as critical for feeding, migration, or overwintering habitats	M_conn
Nonnative trout[3]	Brook and Brown Trout presence	Presence of Brook and Brown Trout in a given patch	N_Brook
Nonnative trout	Lake Trout presence	Habitat size-weighted connectivity of patches to lakes and reservoirs containing Lake Trout	N_lake
Local human influences	Indices of land, water, and pesticide influences	Human Footprint	H_foot
Local human influences	Road density[4]	Density of all roads in a given patch's watershed	Roads
Local human influences	Movement barriers	Presence of barriers that could isolate a patch from other patches or migratory habitats	P_dam
Climate	Prevalence of very cold water	Percentage of stream length comprised of reaches with predicted mean August water temperatures of ≤10 C	V_cold
Climate	Winter high flow	Percentage of stream length comprised of reaches with <2 winter floods (see text for details)	W95
Climate	Wildfire	Percent of patch severely burned within the past 20 years	P_fire
Spatial variability	Indicator	Random effect indicating variability in probability of presence among units	Core area[5]

[3] Brook Trout considered in the Clearwater Basin study only – not quantified for other basins. Brown Trout were not present in the Clearwater basin, and thus were not included herein.
[4] Used to model probability of detection in Clearwater Basin study only.
[5] Evaluating random variability in parameters grouped by recovery unit, critical habitat unit, or core area (see Task 3 methods for details).

Table 3. Hypothesized influences of major covariates (Table 2) on presence of Bull Trout in patches.

Covariate	Hypothesized influences	Predicted effect
Spawning and rearing patch size	Increased demographic stability and decreased vulnerability to catastrophes in larger patches (Rieman and Dunham 2000).	Increasing patch size increases probability of presence.
Spawning and rearing patch connectivity	Greater proximity among local populations should increase demographic support and probability of recolonization following catastrophes (Rieman and Dunham 2000).	Increasing connectivity increases probability of presence.
Migratory habitat size and connectivity	Connectivity to migratory habitats may allow individuals to grow larger and provide greater reproductive contributions and provide a source of colonists following catastrophes in spawning and rearing patches (Rieman and Dunham 2000).	Increasing migratory connectivity increases probability of presence.
Brook and Brown Trout presence	Predation, competition, disease transmission or hybridization (especially Brook Trout) may lead to displacement (Dunham et al. 2002) of Bull Trout.	Presence of nonnatives decreases probability of presence.
Lake Trout presence	Lake Trout in lakes or reservoirs can displace Bull Trout (Donald and Alger 1993), possibly leading to extirpation in spawning and rearing patches.	Presence of Lake Trout decreases probability of presence.
Indices of land, water, and pesticide influences	A host of human influences may threaten Bull Trout including harvest (legal or illegal) and indirect effects of land and water use (USFWS 2002, 2008).	Lower probability of presence in patches with higher index of human influences.
Road density	The presence of roads indicates associated human activity that may negatively influence Bull Trout	Lower probability of presence in patches with higher road density
Movement barriers[6]	Barriers can reduce local population sizes, connectivity among populations, and migratory connectivity.	Fragmentation by barriers decreases probability of presence.
Prevalence of very cold water	Requirements of Bull Trout for reproduction involve very cold water – much more so than used for delineation of an entire patch for spawning and rearing.	Percentage length of cold water streams increases probability of presence.
Winter high flow	High winter stream flows negatively influence survival of early life stages of Bull Trout	Percentage length of streams with winter flooding decreases probability of presence.
Wildfire	Severe wildfire can lead to short or long-term disturbance that extirpates Bull Trout.	Increasing percentage of severe fire decreases probability of presence.

[6] Considered indirectly through the influence of barriers on patches (see Task 1)

Methods

Fish presence. Before attributing patches with predictors (Table 2), we sought to gain information on presence of trout in patches. Information about Bull Trout presence in each patch was derived from the USFWS Final Critical Habitat GIS layer (USFWS 2010). Patches that contained at least one reach that was classified as both “known-occupied” and “spawning-rearing” were given a Y (present). Patches that were sufficiently cold and suitable but did not contain a reach classified known-occupied and spawning-rearing were given an N (not present).

To further refine information on trout presence we developed an attribution tool for local managers to use (Appendix 1). Biologists were asked to estimate the likelihood of Bull Trout spawning-rearing presence in a given patch, using a scale of 0 (no probability of presence) to 1 (extremely high probability of presence). Similar questions regarding the presence of nonnative Brook and Brown Trout were included.

Among the predictors considered (Table 2), we expected *patch size* to be most important. Patch size, or patch length, was calculated as the total length of streams in each patch, in kilometers. As indicated in the discussion of the patching process, streams were filtered to remove small streams.

A number of covariates we derived used patch watershed area, which consists of the entire drainage area flowing into the patch stream lines. Thus, if a patch’s streams do not extend very far upstream because of a dam or other patch-breaking feature, its patch watershed area could be considerably larger than the area surrounding the patch streams.

Connectivity was considered in terms of the size of other patches within a network and their distance from a focal patch. The focal patch was considered to be the patch for which connectivity was calculated. The measure of connectivity we used gave greater weight to non-focal patches that were larger and closer to the focal patch. For example, a small patch that was close to the focal patch could contribute as much to connectivity as a larger but more distant patch. Specifically, connectivity among patches was measured by summing the distance-weighted patch length (A) of every patch *j* connected to the focal patch *i* ($\mathrm{Sum}(A/(d_{ij}+1))$). Stream distances were calculated between the focal patch i (downstream pour point, not the center) and each connected patch (j's) within a NorWeST region (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html), using ArcGIS Network Analyst. (Patches separated by a dam on the National Inventory of Dams list (USACE) were considered to be disconnected.) The reciprocal of the distance plus one (1/d+1) was multiplied by the patch length (stream length, symbolized as "A" above but not meaning area in this case) of the connected patch (not the focal patch). The distance-weighted patch lengths for all connected patches were summed to generate a measure of connectivity for each focal patch.

Migratory habitat size and connectivity was considered in terms of lakes or reservoirs identified as feeding, migration, and overwintering (FMO) areas for Bull Trout habitat (USFWS 2010). Lakes and reservoirs not identified as FMO, but similar to those classified as FMO, were also included in our analysis. To be included in our analysis, non-FMO lakes and reservoirs had to match conditions observed in FMO lakes and reservoirs. The conditions we considered in FMO water bodies included water body surface area, elevation, and the mean modeled summer air temperature over the water body, using the PRISM temperature model (1971-2000; http://prism.oregonstate.edu/; data available online at http://oldprism.nacse.org/products/matrix.phtml?vartype=tmax&view=maps). Information on other features of lakes and reservoirs (e.g., depth, fluctuations in volume) was not available. We calculated the mean and 95% confidence bounds for these FMO characteristics in every FMO water body. We then evaluated these characteristics in non-FMO lakes and reservoirs. If values of all three characteristics fell within the 95% confidence bounds for FMO water bodies, we included them in our calculation of migratory habitat size and connectivity.

Migratory habitat size and connectivity were integrated to provide a measure of habitat complementation for predicting presence of Bull Trout in patches. To integrate size and connectivity, we calculated the distance-weighted surface area of all connected lakes and reservoirs for each patch (including those classified as FMO or matched with FMO as described above). In a process similar to the patch connectivity metric, stream distances were calculated between the focal patch *i* (downstream pour point, not the center) and each connected lake or reservoir within a NorWeST region, using ArcGIS Network Analyst. Lakes separated from a patch by a dam on the Army Corps of Engineers National Inventory of Dams list were considered to be disconnected. FMO lakes within a patch were considered to have a distance of zero. The reciprocal of the distance plus one (1/d+1) was multiplied by the surface area of the FMO lake. The distance-weighted areas for all connected FMO lakes were summed to generate an FMO metric for each focal patch.

Brook and Brown Trout presence were tallied only for watersheds where the patch attribution tool (Appendix 1) was used. Information about the *presence of Lake Trout* was reviewed to identify the 32 lakes in our study area that contain Lake Trout. To determine the presence and size of Lake Trout lakes in relation to the Bull Trout patches, the distance-weighted surface area of all connected Lake Trout lakes was summed for each patch. In a process similar to the patch connectivity metric, stream distances were calculated between the focal patch *i* (downstream pour point, not the center) and each connected Lake Trout lake within a NorWeST region, using ArcGIS Network Analyst. Lakes separated from a patch by a dam on the Army Corps of Engineers National Inventory of Dams list were considered to be disconnected. Lake Trout lakes within a patch were considered to have a distance of zero. The reciprocal of the distance plus one (1/d+1) was multiplied by the surface area of the Lake Trout lake. The distance-weighted areas for all connected Lake Trout lakes were summed to generate a Lake Trout metric for each focal patch.

To assess potential human influences on Bull Trout, we used both road density (road length divided by patch watershed area) and the *Human Footprint Index* (Leu et al. 2008), which incorporates 14 landscape structure and anthropogenic features into seven models to estimate the influence of the human footprint on the landscape. The output metric is a grid with 10 possible classes, from 1 (lowest human influence) to 10 (highest human influence). We used the Zonal Statistics tool to derive the mean Human Footprint Index for each patch basin. Because road density and the Human Footprint Index were correlated, we ended up using Human Footprint Index only in the model.

We considered three climate-linked predictors of the presence of Bull Trout (Table 2). The *proportion of very cold streams* in each patch was measured by calculating the percentage of patch length with mean August temperatures below 10 degrees Celsius. *Lack of winter flooding* was considered in terms of the length of stream reaches (from NHD) within each patch that experienced <2 winter high flow events. This was measured by calculating the percentage of patch length with streams that had a W95 value less than two. W95 stands for Winter 95, or "the number of days in the winter in which flows are among the highest 5% for the year (Wenger et al. 2010; 2011)." The influence of *high-severity fire* on Bull Trout patches was measured by calculating the percentage of each patch watershed that experienced high-severity fire in a 28-year period (1984-2011). Fire severity maps used in this analysis were generated by the Monitoring Trends in Burn Severity (MTBS) project (www.mtbs.gov[7]; Dennison et al. 2014).

Task 3. Modeling presence of Bull Trout

Rationale

Our objective was to determine the role of climate related and other threats to Bull Trout in a manner that permitted spatial patterns in these threats to be identified and quantified. Random effects logistic regression was the simplest way to accomplish this goal; by grouping patches spatially, and allowing regression coefficients among patches to differ from patches located further distant, we could identify areas where individual threats were having more or less influence than average across the species range. So, random effects logistic regression was at the heart of our analytical method. Technically all regression coefficients were allowed in the models to vary by our spatial grouping covariate, and we considered several scales of spatial grouping.

Further, we hypothesized that some of the patches, being newly identified by our patching effort, may not have received as much survey effort as others, or perhaps may have never been visited, resulting in variation in the probability of detecting Bull Trout in patches had they been present. We suspected that patch size and accessibility were likely to affect the probability of detecting the species given it was present and that failing to account for this would result in a biased image of how these same covariates and others affect patch occupancy. For this reason, we coupled the random effects logistic regression models with a model of the detection process. This joint modeling approach of true patch occupancy with a model of detection given occupancy is closely related to Bayesian models developed for photographic image restoration (Bierman et al. 2010). For the joint model to work, we needed additional information, supplemental to known occurrences. We needed information relevant to separating the true underlying pattern of Bull Trout absence from lack of detection due to inadequate survey effort. We used expert opinion to accomplish this, expert opinion of the probability that Bull Trout truly occur where there are no existing records of them occurring. Expert opinion was the only practical way to identify variation in detection probability over such a broad spatial extent.

[7] MTBS Data Access: National Geospatial Data. (2013, August - last revised). MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online:

http://www.mtbs.gov/nationalregional/download.html [2014, March 18].

While the image restoration model was intended, in our assessment of regional threats, to account for variation in the probability of detecting Bull Trout given they were present, it also produces a very useful byproduct. As a byproduct of the joint model, posterior probabilities of species presence are produced for each patch. These posterior probabilities of species presence can be used to identify patches having a high likelihood of presence due to their combination of attributes favoring presence but disfavoring detection. A formal effort may then be made to survey these patches in a way that updates the probability of presence for example.

Methods

Random effects logistic regression – We used a random effects logistic regression model (random coefficients) to relate covariate data to Bull Trout patch occupancy. The grouping covariate was one of several scales of spatial aggregation, allowing the spatial variation of potential threats to be actualized. We evaluated parsimony of different spatial grouping strategies using deviance information criterion (DIC). We eliminated Road Density from inferential models for species presence because the high correlations with several other covariates (Table 4).

Table 4. Pearson correlation coefficients for covariates considered.

Covariate	P_size	Roads	P_conn	M_conn	P_fire	V_cold	W95	H_foot	N_lake
P_size	1.00	-0.10	0.01	0.28	0.34	0.30	0.18	-0.13	0.26
Roadsns	-0.10	1.00	-0.20	-0.02	-0.03	-0.32	-0.39	0.45	-0.01
P_conn	0.01	-0.20	1.00	-0.01	-0.01	0.19	0.18	-0.24	-0.02
M_conn	0.28	-0.02	-0.01	1.00	0.21	0.01	0.01	-0.02	0.24
P_fire	0.34	-0.03	-0.01	0.21	1.00	0.05	0.02	-0.02	0.03
V_cold	0.30	-0.32	0.19	0.01	0.05	1.00	0.42	-0.29	0.02
W95	0.18	-0.39	0.18	0.01	0.02	0.42	1.00	-0.34	0.03
H_foot	-0.13	0.45	-0.24	-0.02	-0.02	-0.29	-0.34	1.00	-0.02
N_lake	0.26	-0.01	-0.02	0.24	0.03	0.02	0.03	-0.02	1.00

Variance inflation factors for remaining covariates (VIFs = 1.41, 1.09, 1.15, 1.17, 1.38, 1.37, 1.35, 1.12) alleviated any concern about potential problems with multicollinearity. Because of the large number of covariates in the model and moderate correlations, we used prior distributions for regression coefficients that promote conservative estimates of covariate effects (ridge regression; Lindley and Smith 1972) – two versions: 1) ridge regression prior distributions on main effects with additive normal random offsets, and 2) ridge regression prior distributions on all 8 covariates*4 recovery units = 32 coefficients. We assessed fit of the most general model using a Bayesian P-value based on the chi-squared goodness of fit test statistic comparing observed and expected numbers of sites having positive detections where similar sites were binned. Binning was done along the first PC score of model coefficients such that expectations within bins exceeded 5. Model fit was good (0.54) as Bayesian P-values near 0.5 indicate well-fitting models whereas values near 0 or 1 indicate poor fit.

Bayesian Image Restoration – With a sub-set of the cold water patches, we assessed the potential influence of variation in the probability of detecting Bull Trout given presence that was associated with remoteness (road density, assuming lower road density leads to lower sampling effort and thus probability of detection) and size of the patches. To accomplish this we fit a joint model for species presence and species detection conditional on presence, capitalizing on elicited expert opinion of the probability of Bull Trout presence at patches having no historical observations in order to identify the two processes. The model is an adaptation of the Bayesian image restoration model of Bierman et al. (2010), wherein effectively logistic regression-type models relate covariate data to the two outcomes (true species presence and detection given true presence). The covariates road density and patch size were included in the model for detection probability given presence. The covariates patch size, human footprint (H_foot), patch connectivity (P_conn), wildfire (P_fire), and winter high flow (W95) were related to true presence. The model for true presence, therefore, includes a subset of the larger number of parameters that were used with the full dataset (the random effects logistic regression, describe above). This was necessary because of the limited spatial extent where expert opinion on presence was available.

6. PROJECT RESULTS:

Random effects logistic regression – We completed analysis based on the four recovery units having NorWesT temperature data available at the time of this study (Mid-Columbia, Coastal, Upper Snake, Columbia Headwaters), comprising 3110 total cold water patches. Of the five logistic regression models considered, information criteria sequentially favored incorporation of finer grain size for spatial clustering (Table 1). The model incorporating random coefficients for 83 core areas was favored based on DIC.

Table 5. Deviance information criterion (DIC) for models of the presence of Bull Trout in four recovery units based on different random coefficients, ranging from none (fixed effects) to clustering by recovery unit, Critical Habitat Unit (CHU), or core area (see USFWS 2008, 2010).

Model	N parameters[8]	DIC
Fixed Effects Ridge Regression	7.9	1717
Ridge regression clustered by recovery unit (4)	25.4	1587
Random Effects clustered by recovery unit (4)	21.5	1591
Random Effects clustered by CHU Area (26)	54.7	1442
Random Effects clustered by core area (83)	104.0	1387

Of the eight covariates included in the most parsimonious model, four had main effect coefficients with 95% credibility intervals that did not overlap zero, indicating strong probabilistic support for the effects across the study extent: patch size (P_size), human footprint (H_foot), very cold (V_cold), and W95 (Table 6). The multiplicative change in the odds of occupancy for a one standard deviation increase in the covariates were 20.3 (10.4, 40.1) for patch size, 0.69 (0.49, 0.93) for human footprint, 1.56 (1.30,

[8] Fractional numbers of parameters are due to random effects being valued differently than main effects.

1.92) for very cold, and 1.56 (1.19, 2.15) for W95, indicating the magnitude of effect sizes relative to the magnitude of variation that exists in the covariate on the landscape. These equate to multiplicative effects on the odds of occupancy of 1.07 (1.06, 1.09) for a 1 km increase in patch size, 0.69 (0.49, 0.93) for a one unit increase in human footprint, 4.55 (2.42, 9.15) for each percent increase in the percentage of stream length comprised of reaches with predicted mean August water temperatures of ≤10 C, and 2.53 (1.43, 4.97) for a one percent increase in percent patch area having less than two high flow events. Means and standard deviations of covariates are presented in Table 6.

Table 6. Summary of posterior distributions of model parameters for the best model, random coefficients for 83 core areas (Table 5). Coefficients are representative of covariates standardized to one standard deviation about the mean.

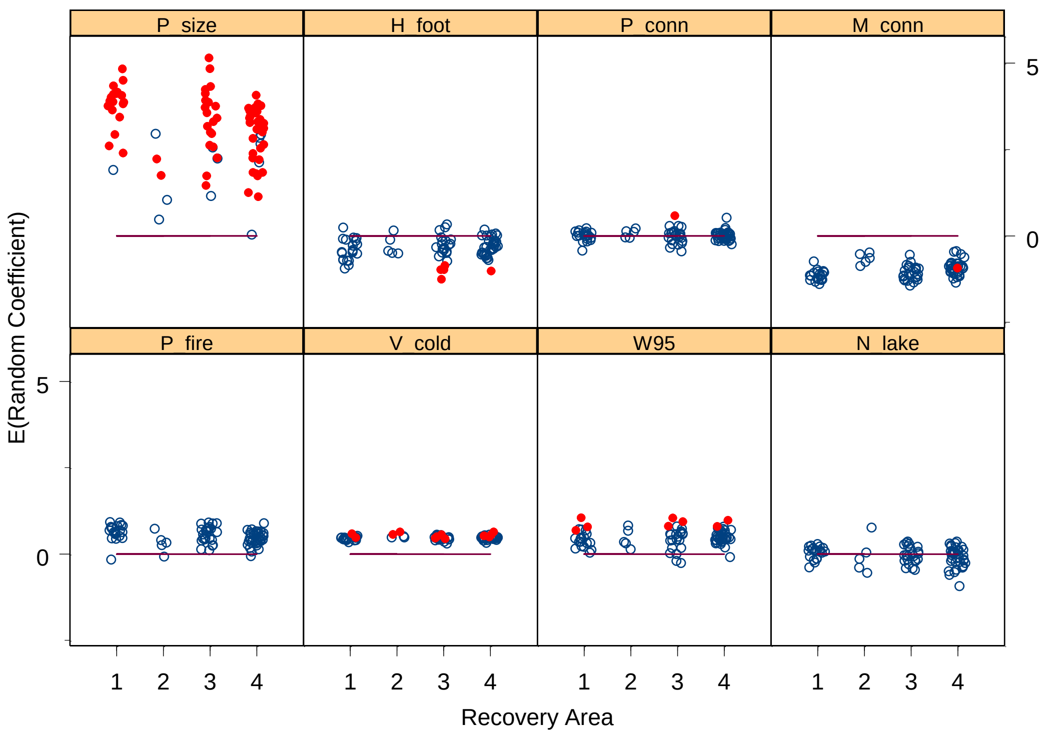
Covariate	Mean	St. Dev	2.5^{th}	25^{th}	50^{th}	75^{th}	97.5^{th}
Intercept	-2.30	0.26	-2.82	-2.47	-2.30	-2.12	-1.78
P_size	3.02	0.34	2.35	2.79	3.01	3.23	3.69
H_foot	-0.39	0.16	-0.72	-0.49	-0.38	-0.28	-0.07
P_conn	-0.02	0.15	-0.32	-0.11	-0.01	0.08	0.29
M_conn	-1.02	0.83	-2.62	-1.62	-1.12	-0.31	0.51
P_fire	0.49	0.50	-0.39	0.14	0.44	0.83	1.56
V_cold	0.45	0.10	0.26	0.38	0.45	0.51	0.65
W95	0.45	0.15	0.17	0.35	0.44	0.54	0.76
N_lake	-0.07	0.37	-0.71	-0.33	-0.08	0.15	0.79

Table 7. Covariate means and standard deviations (St dev).

	P_size	H_foot	P_conn	H_foot	P_fire	V_cold	W95	N_lake
Mean	17.300	2.98	40.76	35.31	473.57	0.236	0.453	8.96
St dev	43.245	1.00	59.52	932.75	6159.16	0.294	0.477	214.64

Variation in random coefficient values among the 83 core areas (Fig. 2) depicts greatest variation associated with the effect of patch size and least variation associated with very cold water. Within the four main effects that were well supported probabilistically, some core area-specific coefficients are not well supported (Fig. 2). Of the remaining covariates having main effects that were not well supported, only a single random coefficient is well supported for patch connectivity (P_conn) and for migratory connectivity (M_conn; Fig. 2).

Figure 2. Variation in random coefficients among core areas within recovery units. Depicted are posterior means of the random core area coefficients grouped for display by recovery unit (1, Mid-Columbia; 2, Coastal; 3, Upper Snake; 4, Columbia Headwaters; core areas nested within recovery areas). Estimates having 95% credible intervals overlapping zero are depicted with open blue symbols, whereas estimates having intervals not overlapping zero are depicted with closed red symbols. Low precision in coefficient estimates in conjunction with substantial shrinkage of random effects to the group mean effects for M_conn and P_fire explain the distance of blue point clusters from 0.

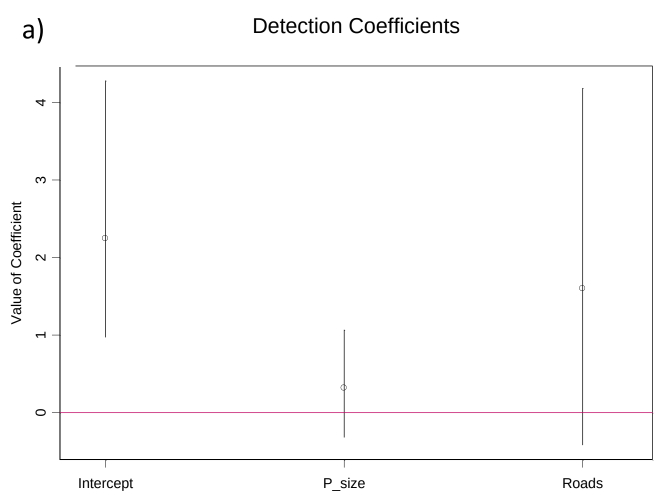


We determined the explanatory ability of the most parsimonious model using Cohen's kappa statistic (Manel et al. 2001) based on a probability of 0.5. Cohen's kappa was computed separately for the four recovery units included in analyses (0.57, Mid-Columbia; 0.45, Coastal; 0.63, Upper Snake; and 0.64, Columbia Headwaters) despite the spatial grouping covariate of the model being of a finer grain size. Values of Cohen's kappa <0.4 represent slight to fair, values 0.4 to 0.6 represent moderate, 0.6 to 0.8 substantial, and >0.8 almost perfect model performance (Landis and Koch 1977).

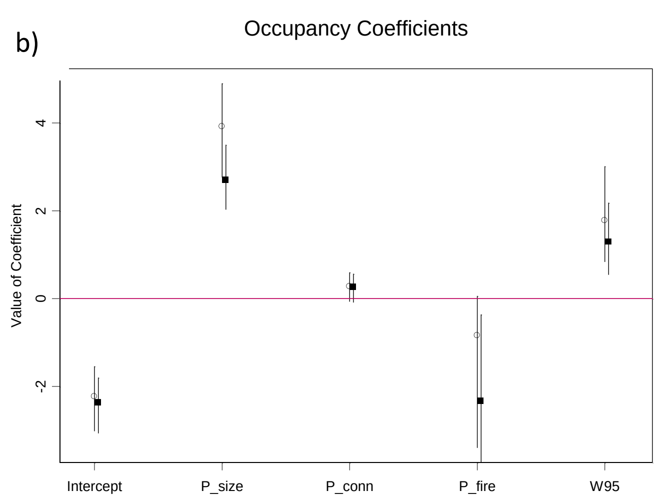
Bayesian Image Restoration – Based on patches attributed using the USFWS Final Critical Habitat GIS layer (USFWS 2010), we identified 64 of the 348 patches in the Clearwater River basin that could be classified as occupied. Patch attribution via expert opinion (Appendix A) identified 26 additional patches (classified as > 0.5 probability of presence of Bull Trout spawning and rearing). Using only the Clearwater data, and fixed effects model incorporating expert opinion of probability of presence for patches having no record of presence, patch size and road density both were weakly associated with higher probability of detection conditional on presence (Fig. 3a). Using this reduced data set and subset of covariates, the effect of ignoring detectability on the regression coefficients for patch occupancy affected the magnitudes but not directions of effects (Fig. 3). Including Brook Trout presence in the model for patch occupancy produced a positive coefficient [coefficient = 0.094 (-0.328, 0.6181; lower and upper 95%CI)] but its 95% credible interval broadly overlapped zero. All patches in the Clearwater data set were classified as having 0.0 probability of Brown Trout present.

Figure 3. Estimates of regression coefficients associated with probability of detection given presence (Panel a), and patch occupancy (Panel b) using the Bayesian image restoration model incorporating expert opinion priors for the probability of Bull Trout presence at patches having no record of presence (open symbols). Estimates based on logistic regression (ignoring detectability) are included in panel b as closed symbols.

a)



b)



7. ANALYSIS AND FINDINGS:

Factors related to presence of Bull Trout

Patch size. Presence of Bull Trout in patches across the domain that we modeled was most strongly tied to patch size. From an ecological perspective, patch size may be expected to be a strong driver of presence as larger patches should support a broader diversity of habitat conditions, and more importantly be more likely to support conditions that are suitable for Bull Trout in the face of disturbances, such as those related to wildfire (Dunham et al. 2003; Luce et al. 2013; Falke et al., in press). Larger patches may also support larger populations, which are less vulnerable to extinction in the face of genetic, demographic, and environmental stochasticity (Gilpin and Soulé 1988; Rieman and McIntyre 1993; Caughley 1994).

A plausible alternative explanation for the association between patch size and presence is the simple expectation that larger patches may more likely be sampled more intensively by virtue of their larger size. Consider the simplest case of random sampling points distributed across the range of Bull Trout. Larger patches will be more likely to be allocated more points, and thus sampling effort. Increased sampling effort should lead to increased probability of detection, and lead to an association between probability of presence that is more related to probability of detection than to ecological factors influencing presence or persistence (Peterson et al. 2002; Peterson and Dunham 2003). Our comparison of a fully attributed patch model based on expert attribution versus attribution of presence based on USFWS (2010) data on Bull Trout presence suggested that sampling bias did not substantially influence model bias in the Clearwater Basin, but we cannot rule out this possibility in some areas. Even without sampling bias, the null expectation based on a random distribution of fish across the landscape would be that Bull Trout are more likely present in larger patches. Again, we cannot rule out this possibility, but given the number of plausible alternative biological explanations for the relationship between patch size and persistence cited above, it seems likely that patch size has a mechanistic link to persistence of Bull Trout.

Additional use of the patch attribution tool developed herein, or a variant thereof could be used to improve predictions of presence for Bull Trout across the species range. This would require only a minimal investment of effort and no field work using methods developed herein (Appendix 1). Alternatively, models developed here could be used to more efficiently prioritize sampling of patches in the field to classify them as occupied or not following previous protocols (Peterson and Dunham 2003), which have been applied in many situations on the ground for Bull Trout (e.g., Dunham et al. 2011) and other species (Jolley et al. 2012).

Very cold water. The strong link between the presence of very cold water (<10^{o}C, predicted mean August stream temperature) could be explained by several factors. Bull Trout require very cold temperatures for egg incubation (McPhail and Baxter 1996), but spawning occurs in late August and throughout the fall season. Thus, the association between presence of Bull Trout and very cold water cannot be explained by spawning alone. For example, there is evidence to suggest that the viability of eggs developing prior to spawning is related to colder water temperatures (McCullough et al. 2009). Furthermore, Bull Trout may be able to better coexist with salmonids with less cold-adapted physiology when temperatures are very cold (Paul and Post 2001; Rieman et al. 2006; McMahon et al. 2007). Although Bull Trout may perform relatively well in very cold water, growth of Bull Trout is maximized at temperatures above 10 ^{o}C when rations are not limited (Selong et al. 2001; Mesa et al. 2013). Field observation suggests individuals often use warm water (>20 ^{o}C) for feeding or migration, at least for short periods of time (e.g., Howell et al. 2010). These observations suggest that conditions most suitable for growth, gamete development, and egg incubation, may vary among these different responses and explain much of the spatial and temporal variability observed in temperatures used by Bull Trout in the field (Dunham et al. 2008; Eckmann 2014). Accordingly, it seems likely that thermal requirements of Bull Trout cannot be simply described in terms of a few physiological thresholds (Poole et al. 2004). A better understanding of how temperature translates into growth, survival, and reproduction of Bull Trout in the context of species interactions and other factors is needed.

Flooding in winter. Based on the results of earlier studies relating presence of Bull Trout to winter high flows, we selected a measure of flow (W95; Wenger et al. 2010) that we assumed to represent flows that would potentially displaced recently emerged juveniles, rather than flows of sufficient strength to mobilize stream sediments and scour or displace redds, embryos, or alevins (Wenger et al. 2011). As with previous work conducted at sites (Wenger et al. 2011) we found that lack of high flows in winter was positively associated with presence of Bull Trout.

Human footprint. The Human Footprint index (Leu et al. 2008) proved to be a useful predictor of the absence of Bull Trout across the extent we studied. This index is linked strongly to the presence of urbanized area, agricultural lands, and secondary roads. Past work has linked absence of Bull Trout to the density of roads alone (Rieman et al. 1997; Dunham and Rieman 1999) and measures of land use (e.g., forest harvest; Ripley et al. 2005), collectively suggesting a consistent negative association between the status of Bull Trout and presence of human influences linked to roads and other land or water uses. We were unable to break human influences down into more specific categories of effects. For example, roads are a human influence that can indirectly influence fish through a multitude of pathways (Trombulak and Frissell 2000). More generally information on specific pathways through which patterns of land use or development influence aquatic habitats can be challenging to derive, as much critical local information is missing (e.g., information on locations or characteristics of passage barriers; Januchowski-Hartley et al. 2013) or complex pathways of influences (e.g., Poole and Berman 2001).

Spatial variation in responses. The effects of patch size, very cold water, flooding in winter, and the human footprint varied considerably among core areas, indicating strong local variation in the effects of each of these covariates on presence of Bull Trout. Variability was most pronounced for patch size, indicating that critical patch sizes for persistence vary across the range of Bull Trout. The implication is that extrapolation of critical patch sizes from a single location (e.g., the Boise River; Dunham and Rieman 1999) or uniform rates of habitat loss across the species' range (e.g., Rieman et al. 2007) can be refined by using these location-specific parameters. By contrast, the prevalence of very cold water within a patch exhibited relatively low spatial variation in its relationship with the presence of Bull Trout.

Other factors were intermediate in terms of spatial variability, but with a higher prevalence of core areas with coefficients overlapping zero, indicating no significant relationship with presence of Bull Trout in many localities (core areas). Overall, it is clear that factors representing threats or indicators of threats to Bull Trout vary strongly in their influences across the species' range. Assessments of threats to Bull Trout would benefit by considering the processes behind this high degree of local variability, as opposed to assuming that threats operate uniformly. It is also worth noting that the overall multiplicative effects of these covariates on the odds of presence varied substantially, and were especially large for the prevalence of very cold water, again highlighting the importance of this covariate, in addition to patch size, to presence of Bull Trout.

Covariates not associated with presence. Absence of an association between predictors considered herein and presence of Bull Trout does not suggest they are not important. The importance of some covariates may depend on the scale at which they are considered (e.g., nonnative species; Melbourne et al. 2006), how they are measured, and how they actually relate to or indicate direct threats to Bull Trout. These caveats aside, it was interesting to note that connectivity among patches, migratory connectivity, presence of nonnative Lake Trout, and fire history were not important for explaining presence of Bull Trout across our study domain. The importance of connectivity among occupied patches has been the topic of debate in the literature. Whereas prior ecological studies have found that connectivity among patches can explain presence (Dunham and Rieman 1999), direct observation of movements suggests little switching of tributaries during spawning (e.g., Swanberg 1997; Starcevich et al. 2012), and more definitively a host of studies of gene flow in Bull Trout suggests strong isolation, even among adjacent localities (e.g., Kanda and Allendorf 2001; Taylor et al. 2001; Meeuwig et al. 2010; Ardren et al. 2011). Furthermore, it is not clear that such limited levels of movement have any demographic relevance (Lowe and Allendorf 2010) or strongly influence broad-scale patterns of presence as considered herein. This general finding does not suggest connectivity among local populations is irrelevant in every locality or in situations where connectivity is disrupted by exceptional circumstances (e.g., large natural disturbances, human disruption of natural connectivity) that may force fish to disperse to new locations.

Contrary to our expectation, connectivity to migratory habitats used for feeding, migration, and overwintering was not associated with presence of Bull Trout in patches. A possible explanation is the lakes and reservoirs that we considered for migratory connectivity often represented habitats that have been strongly altered in ways that negatively influence Bull Trout. This seems likely as lakes and reservoirs are often heavily used by humans and may provide a source of invasive species that negatively influence Bull Trout (e.g., nonnative trout; Bahls 1992; Dunham et al. 2002, 2004), and can experience variable water quality and quantity as they can serve a variety of uses, including recreation, water supply, hydropower generation, and flood control (Miranda et al. 2010). The general absence of an association between migratory connectivity and presence of Bull Trout in patches does not mean such habitats are a fundamental liability for Bull Trout. Indeed, there are many such habitats in which Bull Trout thrive, given appropriate conditions (USFWS 2008). As for the case of the Human Footprint, limited availability of specific information on lakes and reservoirs and their pathways of influence on Bull Trout limited our ability to evaluate them in more detail. Development of standardized classifications of lakes based on presence of native and nonnative species, water quality and quantity, trophic status, and other features would prove useful to understanding more about why some lakes and reservoirs support strong populations of Bull Trout, whereas others may prove to be more of a liability than an asset to local populations.

Lack of association between presence of Bull Trout and connectivity to migratory habitats supporting Lake Trout was unexpected, given the strong influence of Lake Trout on declines in Bull Trout populations (Donald and Alger 1993; Fredenburg 2002; Martinez et al. 2009; Meeuwig et al. 2011). Again, whereas Lake Trout have been clearly implicated in local extirpation of Bull Trout in many cases (e.g., Fredenberg 2002), there may be other cases where Bull Trout have persisted, albeit at reduced population sizes, in the face of invasion by Lake Trout. The species naturally overlap in parts of their range that include the Saskatchewan basin (Scott and Crossman 1973 suggesting natural coexistence is possible at a broad scale. It is also possible that the influence of Lake Trout may take several decades to manifest itself in terms of presence of Bull Trout. For example, an initial decline in Bull Trout populations following introduction of Lake Trout may be followed by a long period of reduced numbers of Bull Trout, which ultimately may be more vulnerable to other threats which could result in local extirpation (e.g., Gilpin and Soulé 1988; Rieman and McIntyre 1993). Learning more about factors contributing to natural coexistence of these species and threats that may lead to local extirpation in populations of Bull Trout depressed by Lake Trout invasion are critical information needs.

Lack of association between recent wildfires and Bull Trout was not unexpected, although wildfire activity has increased over the time period we considered (Westerling et al. 2006; Dennison et al. 2014). In the context of historical fires (10^3 years) the time period for which we had information may be less relevant, and it is possible that contemporary presence of Bull Trout in some locations may be tied to historical events that were much larger than we have recently observed or will observe in the future as regional climates warm. Although the debate over linkages between wildfires and climate continues (e.g., Fulé et al. 2014; Williams and Baker 2014) there is little question that fire can pose a threat, particularly to Bull Trout occupying smaller patches with a high probability of a severe fire (Falke et al., in press), or otherwise influenced by threats operating prior to a fire (Dunham et al. 2003).

Predictions of species presence

We were able to successfully map and model patterns of presence of Bull Trout across a very broad extent, but unable to capture the important influences of local factors that are difficult to capture in large databases. To better illustrate this, we constructed maps of presence of Bull Trout across the domain that we studied (Figure 4a, b, c). Of particular interest were cases in which the model predicted an outcome that was at odds with existing information on the presence of Bull Trout. Though we cannot expect the model to perfectly predict presence in every case, we found deviations from model predictions to provide useful insights.

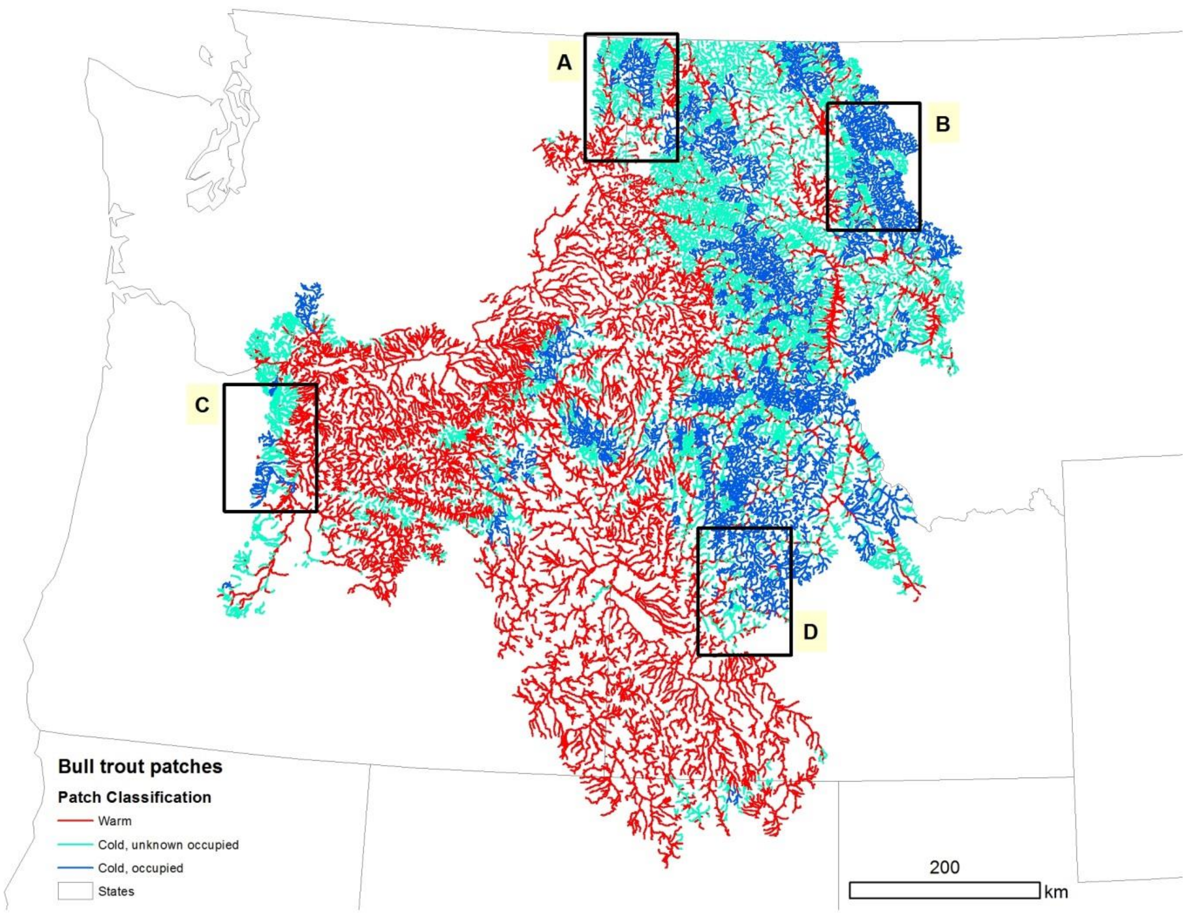


Figure 4a. Location of areas where patterns of Bull Trout presence and model predictions are viewed in more detail (Figures 4b, and 4c, respectively). Area A largely represents the western side of the Lake Pend Oreille and Priest River watersheds and the Pend Oreille River flowing north to the Canadian border. Area B largely represents the South Fork Flathead River and the Swan River basin in northwestern Montana. Area C largely represents the lower Deschutes River basin in north-central Oregon. Area D largely represents the Boise River basin in southwest Idaho. Red lines indicate streams with temperatures too warm to be classified as patches, whereas light and dark blue lines indicate streams with temperatures cold enough to be classified as patches and with unknown occupancy (light blue) or known occupancy (dark blue).

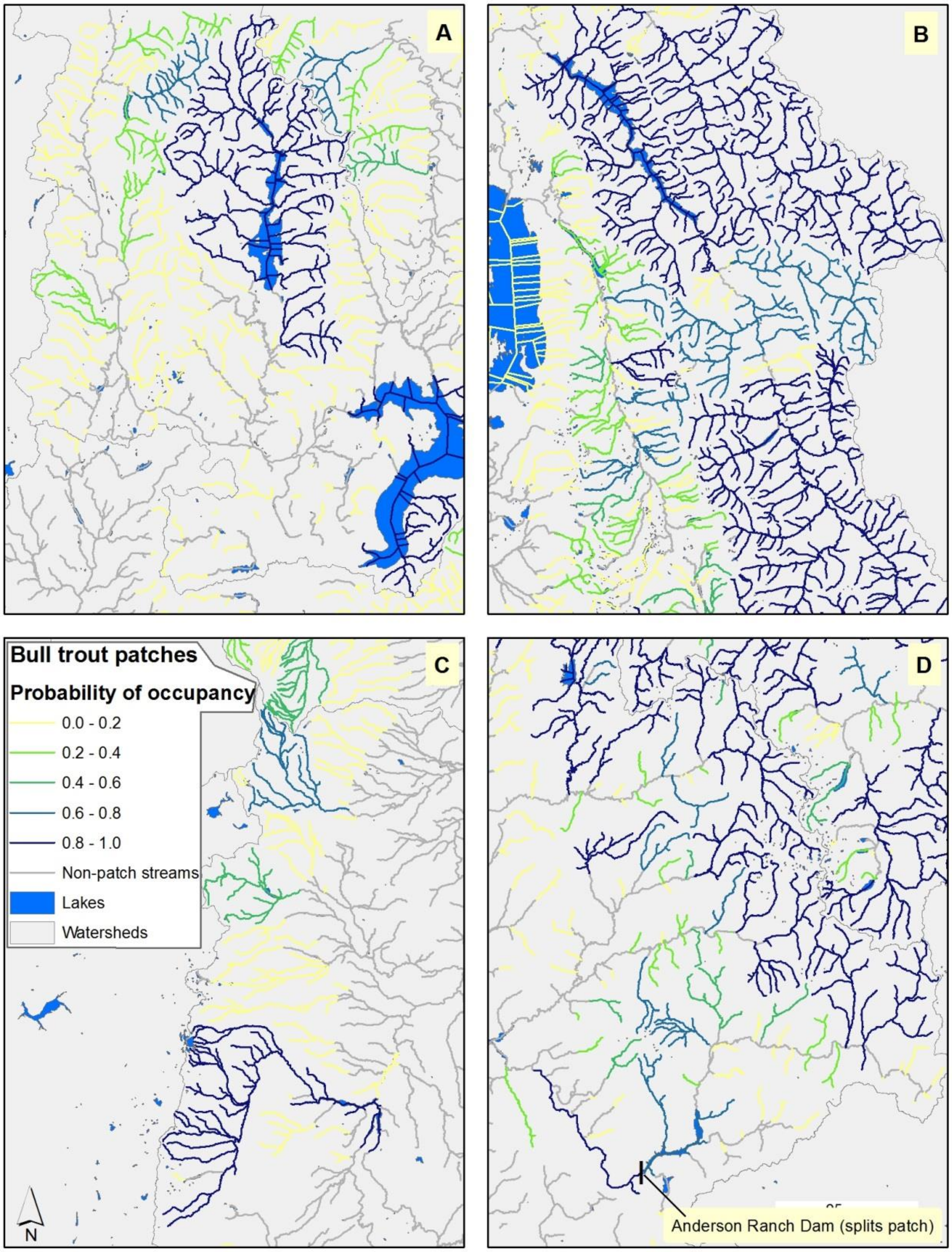


Figure 4b. Close-up view of four areas (Figure 4a) illustrating patterns of model-predicted occupancy for Bull Trout in patches.

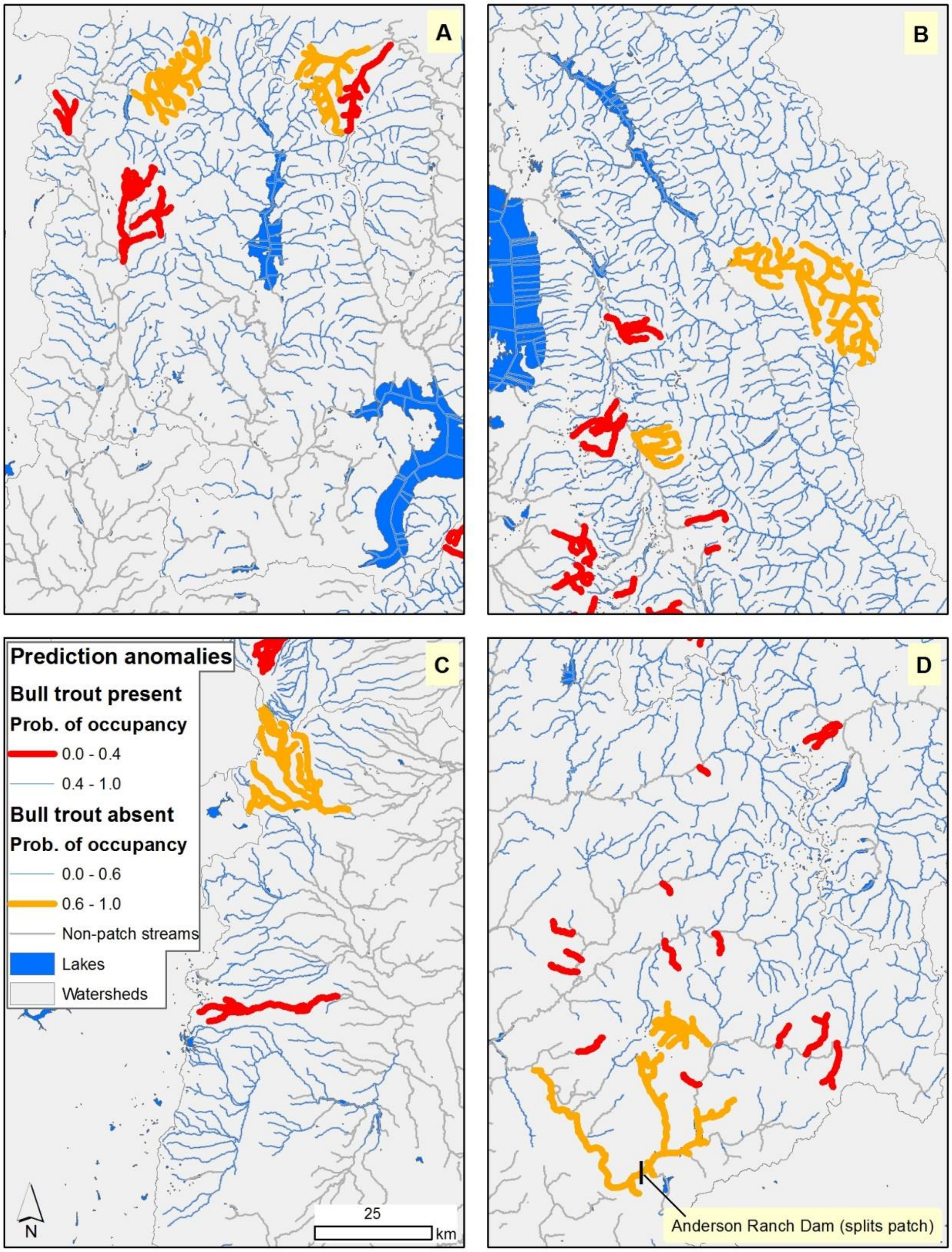


Figure 4c. Close-up view of four areas (Figure 4a) illustrating predication anomalies in patches, including cases with Bull Trout classified as present, but predicted to be absent and Bull Trout not known to be present ("absent" in the legend) and predicted to be present. In each of the four cases evaluated (Figure 4c), prediction anomalies were particularly instructive with respect to revealing important local features that were not captured in the broad scale analysis. For example, in the lower Pend Oreille

system upper Sullivan Creek (left of center in the top of Figure 4c.A.) was predicted to support Bull Trout, but Bull Trout are not known to be present in that system (USFWS 2012). This section of stream is above a human-constructed and natural barrier to fish movement, thus potentially explaining the absence of Bull Trout in this system. This particular stream is under consideration for a potential reintroduction of Bull Trout (USFWS 2012; Dunham et al. 2014). In the South Fork Flathead system, Bull Trout are absent from the upper Spotted Bear River (right of center in Figure 4c.B), where a known natural waterfall has prevented colonization (USFS 2013). In this case the model predicts that Bull Trout would likely be present in the absence of this barrier. In the lower Deschutes River, Bull Trout is similarly predicted to be present in a presently unoccupied patch upstream of a natural barrier in the White River. Notably in this basin, Shitike Creek, a major extant local population is predicted to be absent, which may be an indication of the threatened status of that population. Finally in the Boise River basin Bull Trout is predicted to be present in the mainstem South Fork Boise River downstream of Anderson Ranch Dam. This artificially cold reach of stream supports a robust fishery for Rainbow Trout and based on telemetry studies also attracts a number of Bull Trout, which may now reproduce in that system, although spawning has yet to be observed (Salow 2005; Maret and Schultz 2013; D. Vidergar, U.S. Bureau of Reclamation, personal communication). Upstream of Anderson Ranch Reservoir, the model predicted presence in two currently unoccupied streams listed by USFWS as potential spawning and rearing habitat (USFWS 2002). We do not know if bull trout were present historically in these streams, but it is worth hypothesizing that historical presence may be more likely in these streams, relative to those where the model predicted bull trout to be absent.

Across the range of Bull Trout cases where Bull Trout were present and predicted to be absent were largely in smaller patches, whereas cases where Bull Trout were not known to be present and predicted to be present were in larger patches (Figure 5). This is largely a result of the dominant influence of patch size on presence of Bull Trout.

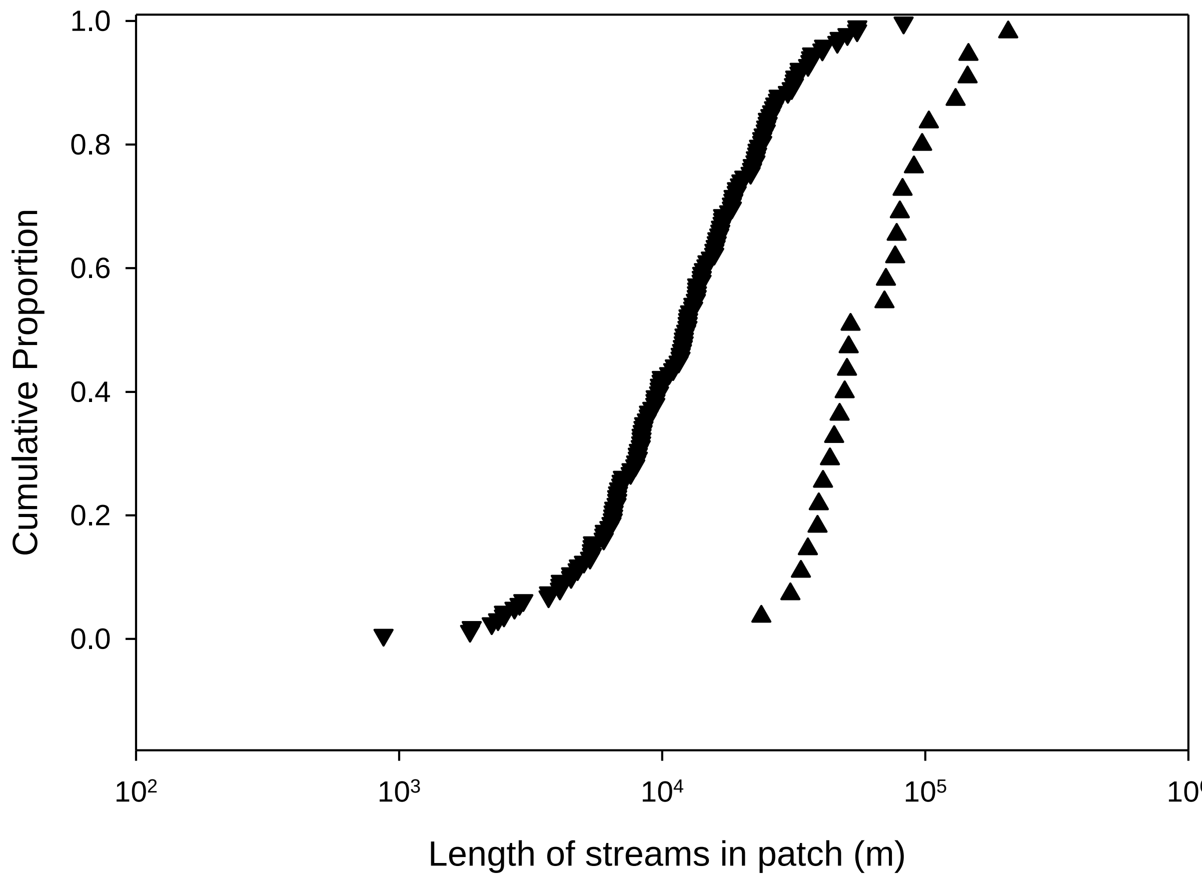


Figure 5. Cumulative proportion of anomalies where patches with Bull Trout were predicted to be absent by the model (downward pointing triangles) and where patches with unknown occupancy were predicted to be present (upward pointing triangles).

Implications for understanding climate vulnerability

The vulnerability of a species to climate change can be defined in terms of how sensitive it is to factors influenced by changing climates (including climate variability), the degree to which these factors may be anticipated to change or their rates of change, and the capacity of the species to adapt to these changes (Füssell and Klein 2006). We found the most important physical factors that influence Bull Trout are temperature and stream flow. Both of these are expected to respond to climate change, but the exact degree to which each will change depends on a host of uncertainties. Although climate enforces a coherent response among streams, there are local factors (e.g., shading and subsurface processes in the heat budgets of streams) that can play a substantial role in driving trends as well (e.g., Isaak et al. 2012; Mayer 2012; Arismendi et al. 2013; Luce et al. 2014). Changes for stream flow regimes are more certain in the form of increasing probability of higher flows occurring in winter (Wenger et al. 2010) because snow packs are widely predicted to decline across the western United States (Nolin and Daly 2006). Climate-related habitat loss for Bull Trout has been projected based on increasing air temperatures (Rieman et al. 2007), but it is well-known that raw projections of air temperatures or use of common regression-based methods can be subject to inaccuracies (Johnson 2003; Arismendi et al. 2014). Under the most extreme scenarios of change, however, these uncertainties will be less relevant (Wenger et al. 2013). Ultimately it is important to keep in mind that the effects of historical and contemporary local human influences on Bull Trout habitat may equal or exceed effects projected in the face of climate change (e.g., Bisson et al. 2009). Ultimately, regional changes to availability of habitat for Bull Trout will interact with local human influences to determine the species' future. Information from models generated in this work will prove useful at both extents, and allow local managers the ability to identify on-the-ground actions to increase the resilience of Bull Trout in the face of climate change (e.g., Falke et al., in press).

8. CONCLUSIONS AND RECOMMENDATIONS:

Products from this effort provide a consistent framework that will be useful for evaluating management priorities and the status of Bull Trout across the species' range within the conterminous United States. Applications of products from this work will also prove useful within local watersheds, core areas, recovery units, or other locally delineated conservation unit (e.g., Falke et al., in press). We encountered several limitations in this project. Most notable among them are the following:

- Lack of a consistent attribution of presence of nonnative trout, especially Brown and Brook Trout, across the species' range. More widespread use of the fish presence attribution tool presented here (or future modifications of the tool) is a simple and low-effort solution to addressing this major information gap.
- Lack of time for managers to use the attribution tool. Although we were able to provide simple and readily useable tools for patch attribution, most managers we approached lacked the time to use the tool. With declining agency budgets, personnel, and increasing demands on time, this is an understandable problem. That said, attributing the Clearwater patches took less than two days of time. We hope this example will motivate others in the future to allocate some time to patch attribution.
- Lack of information on local connectivity. We were not able to locate a consistent database that provided adequately spatially referenced data for waterfalls, diversions, culverts, or other local barriers to fish movement in stream networks. Such information would obviously prove valuable for this effort, as well as for a host of other management applications. Many of the prediction errors we specifically examined in our modeling effort (Figure 4c) were linked to lack of local information on connectivity.
- Lack of precision in measures of human influence. More specific information linked to human influences that can potentially influence habitat or Bull Trout directly would be useful. Our analysis showed that Bull Trout respond strongly to the general human footprint on the landscape, but we were not able to resolve how specific threats (e.g., angling, land uses, water uses) were operating. In particular the specific condition of habitats used for feeding, migration, and overwintering would

be useful. For example, we searched extensively for a unified database describing conditions in major lakes and reservoirs throughout the range of Bull Trout, but no such information seems to exist.

- Limited time available to complete this project. Although the life of the project has extended over four years to date, the extensive effort required to complete temperature modeling and mapping (e.g., the NorWeST effort) and to assemble data for this effort did not allow us to complete the entire range of Bull Trout within the conterminous United States. Accordingly progress reported herein represents part of an ongoing effort and we are actively seeking funds to complete the entire species' range. Large efforts such as this one cannot be completed on timelines that are typically associated with reporting requirements of many funding sources (1-3 years). A major challenge in projects like this is in assembling sufficient funding in the midst of an ever-dynamic institutional landscape of funding availability, priorities, and administrative requirements. Such issues are not unique to this study and even pose challenges for monitoring carbon dioxide levels on Mauna Loa, Hawaii – arguably one of the most important time series ever collected by humankind (Sundquist and Keeling 2009).

9. MANAGEMENT APPLICATIONS AND PRODUCTS:

A critical piece of this effort was to go beyond simply communicating products to managers and to ensure that products are directly incorporated into management actions. To this end, we assembled a group of Regional-level biologists from U.S. Fish and Wildlife Service and the U.S. Forest Service to discuss the assessment and management applications (principal contact: Stephen Zylstra, U.S. Fish and Wildlife Service). This effort involved an in-person meeting at the Regional U.S. Fish and Wildlife Service Office in Portland, Oregon, and several follow-up conference calls.

Patch maps from this effort have been applied to Forest planning on the Lolo National Forest in Montana (Scott Spaulding, Region 1 Fisheries Biologist, personal communication), in the Wenatchee River basin (Falke et al., in press), and in the lower Pend Oreille River in conjunction with relicensing of Boundary Dam operations (Dunham et al., in revision).

Many (15-20) conference calls and in-person meetings with managers and stakeholders in the Klamath (principal contact: Nolan Banish, U.S. Fish and Wildlife Service), Malheur (principal contact: Erica Maltz, Burns Paiute Tribe), Yakima (principal contact: Judy Neibauer, U.S. Fish and Wildlife Service), and lower Pend Oreille (principal contact: Erin Britton-Kuttel, U.S. Fish and Wildlife Service) basins were convened to develop direct applications of patch maps and models of Bull Trout presence for local assessments of threats, opportunities, and management actions. These four basins may serve as case studies for application of products from this work for conservation planning. At the time of this report, work in the Klamath and lower Pend Oreille basins was initiated, with strong interest in the two other basins and efforts initiated to fund work within them.

Specific **actionable items** from these efforts include the following:

- *Climate adaptation*. Generally the most important factor associated with presence of Bull Trout is availability of cold water. Declines in availability of cold water are likely if regional climates warm substantially, but these may be offset by local land and water management practices that also warm water (Poole and Berman 2001). In fact many of these local factors may equal or exceed changes expected from those caused by changing climates (Diabat 2013). Availability of cold water, combined with modeled influences of Bull Trout, and information on local factors influencing thermal loading of streams, can be used to effectively prioritize land and water uses to provide thermal conditions that can support the species in the face of climate change. We have provided one such example for the case of wildfire management and Bull Trout (Falke et al., in press). Management activities associated with wildfire represented an annual federal investment of almost 3 billion dollars in 2012 (Bracmort 2013).

- *Control of nonnative species*. Nonnative Brook Trout is believed to represent a threat to Bull Trout in many portions of the species' range (USFWS 2008). In the Klamath and Malheur basins, we are confronting this issue. Although presence of Brook Trout was not a covariate we were able to consider here (except for the Clearwater River basin, where the patch attribution tool was applied), it is possible to construct local decision support models that incorporate other sources of information on threats from Brook Trout, in concert with estimates of influences of covariates modeled herein (e.g., Peterson et al. 2013). Direct control of Brook Trout can involve intensive effort and a long-term investment of resources (Buktenica et al. 2012). How successful will these efforts be in the face of climate-related changes over longer time horizons (Wenger et al. 2011; 2013)? As with wildfire, modeled predictions of the presence of Bull Trout can be applied to addressing this difficult question. This question is being actively pursued in the Klamath basin and a topic of great interest and likely future investment in the Malheur basins.
- *Connectivity*. The question of connectivity as related to natural barriers, large dams and smaller human-constructed barriers such as road culverts is actively under consideration throughout the range of Bull Trout (USFWS 2008). A recent assessment linked to products from the work presented here has been completed (Dunham et al., in press), and additional work is planned in other locations where dams and dam-related influences on Bull Trout are a major factor (i.e., the Yakima River basin).
- *Monitoring and evaluation*. Past work on Bull Trout has provided a useful view of the current status of critical habitat and species' presence (USFWS 2010), but results from this effort provide a more comprehensive and quantitative view of habitat and species' status. Although species' presence is just one factor that may be considered in evaluation of status or in monitoring, it is critical. Models, maps, attribution tools, and other products developed here can be directly applied to monitoring and evaluation of Bull Trout. In particular, past tools we have developed (e.g., Peterson and Dunham 2003), as well as new methods of surveying for the presence of bull trout (e.g., Wilcox et al. 2013) are ideally suited for working with products from this effort.

Recovery planning. Throughout this project we have made extensive efforts to communicate our work to practitioners, with a focus on recovery planning (principal contact: Grant Canterbury, U.S. Fish and Wildlife Service). The 2014 draft recovery plan for Bull Trout developed by U.S. Fish and Wildlife Service (http://www.fws.gov/pacific/bulltrout/) has directly cited our work and looks to incorporate it directly into recovery planning (page 129):

“Results of currently ongoing analyses for a new stream temperature data collection, modeling and mapping project, NorWeST (USFS 2014), and the Bull Trout Vulnerability Assessment, which will model probability of bull trout presence and map suitable habitat patches using data on stream temperature, fish presence, local threats, connectivity, and climate sensitivity (J. Dunham in litt. 2013). These models are anticipated to be completed over the much of the range of bull trout during 2014. In several core areas we expect local applications of these models to provide detailed analyses that should also help to prioritize management actions in the RUIPs. Potential climate change impacts, while not specifically assessed as an independent threat, will be considered in the context of climatic influence on other threats when determining what recovery actions are needed in core areas.”

10. OUTREACH:

Presentations – Over 30 presentations (too many to list individually) were delivered to describe this work. The majority of presentations were delivered to various regional and local federal and state managers within the range of Bull Trout. An example presentation is posted online: http://www.youtube.com/watch?v=xqLForPz12Y. The project was also featured in presentations to the American Fisheries Society, Western Division Annual Meeting in 2013 and 2014, and the *Salvelinus confluentus* Curiosity Society Meeting in 2012, 2013, and 2014.

Publications -

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Dunham, J.B., D.P. Hockman-Wert, N.D. Chelgren, M.P. Heck, S.J. Wenger, and D.J. Isaak. In prep. Vulnerability of Bull Trout to climate change at the southern margin of its range in the conterminous United States. Canadian Journal of Fisheries and Aquatic Sciences.

11. APPENDICES

Appendix A. Tools for attributing patches with presence of trout based on expert opinion.

A1. Sample memo to local biologists

December 31, 2013

United States Department of the Interior

U.S. GEOLOGICAL SURVEY

Forest and Rangeland Ecosystem Science Center 3200 SW Jefferson Way

Corvallis, OR 97331

From: Jason B. Dunham, Ph.D., Supervisory Aquatic Ecologist (jdunham@usgs.gov) Mike Heck, Fisheries Biologist (mheck@usgs.gov)

To: Bull Trout biologists

Re: Rangewide vulnerability assessment for Bull Trout: request for local data

Thank you for considering our request for assistance in acquiring local trout data in support of our rangewide vulnerability assessment for Bull Trout. The assessment is a massive undertaking to develop data and tools for evaluating threats from local human influences and climate change across the species' range. Contact Mike Heck for a detailed copy of the study plan.

The first steps in this effort have involved expanding a regional effort (NorWeST) to model and map water temperatures in stream networks across the range of Bull Trout. Using the modeled temperature data we are mapping patches of habitat with potential to support Bull Trout. Patches are continuous stream networks, delineated by cold water, that are theoretically capable of supporting Bull Trout. We view patches as the most fundamental unit for planning species recovery and climate adaptation (Dunham et al. 2002).

Using pre-existing data from recent status reviews, many patches have already been attributed with Bull Trout presence. However this effort has also revealed hundreds of patches for which we have little to no fish data. We are requesting your assistance to help attribute these patches where we are uncertain about Bull Trout presence. Please refer to the subsequent pages for a questionnaire regarding presence of bull, Brook, and Brown Trout in cold water patches and instructions on how to attribute these patches. You will use Google Earth to locate and distinguish the patches, and a spreadsheet to record your answers to the questionnaire.

Once the fish data is in place we will model the probability of Bull Trout presence in patches, based on patch characteristics (e.g., patch size, connectivity, habitat quality, presence of nonnative species). We will employ a Bayesian approach that will use the data you provide as "prior" probabilities in the analyses. If you have questions about the methods or the analysis, please contact us.

Again, we wish to emphasize the importance of your assistance and our appreciation for your effort. The temperature models we developed required coordination from hundreds of individuals across the Pacific Northwest. The Bull Trout vulnerability assessment is an effort to make use of this hard-won information and its success depends on your support and knowledge.

A2. Questionnaire for attribution of trout presence in patches

Bull Trout Patch Attribution Questionnaire

- Patches are grouped by 4th Field HUC (Figure 1).
- Answer the following questions for all patches in the HUCs that you have any knowledge of.

1. What is the probability that spawning or rearing Bull Trout were present in patch i in the last 20 years?

–Assign a number between 0 (absent) and 1 (present), based on your level of certainty that spawning or rearing Bull Trout were present in patch *i*.

–Take into account your knowledge on Bull Trout life history and habitat needs, the level of survey effort that has been expended in the patch, and historical records.

–Patches where Bull Trout were known to occur from recent surveys or incidental observation should be assigned a 1. Conversely, patches where Bull Trout were absolutely absent based on many repeated surveys or extremely unsuitable habitat should be assigned a 0.

2. What is the probability that Brook Trout of any life form were present in patch i in the last 20 years?

–Assign a number between 0 (absent) and 1 (present), based on your level of certainty that Brook Trout were present in patch *i*.

3. What is the probability that Brown Trout of any life form were present in patch *i* in the last 20 years?

–Assign a number between 0 (absent) and 1 (present), based on your level of certainty that Brown Trout were present in patch *i*.

Figure 1. Map of 4th field HUCs for the Clearwater Basin, north-central Idaho.

A3. Bull Trout Patch Attribution Instructions

Tools/Files

- Vulnerability_Assessment_Intro_Questionnaire_Instructions.pdf (Appendix A2, above)
- ClearwaterBasin.kmz (patch map in Google Earth format)
- ClearwaterBasin_AnswerForm.xls (Excel spreadsheet for recording responses)
- Google Earth (software to display .kmz files)

Patch Attribution Instructions

1. Download and install Google Earth, if necessary.

2. Download ClearwaterBasin.kmz and ClearwaterBasin_AnswerForm.xls and save them to a known location.

3. Navigate to the folder where you saved the files and open ClearwaterBasin_AnswerForm.xls.

– This will be where you record your responses to the Questionnaire.

– Each HUC has its own worksheet (see tabs at the bottom).

– Address all patches in the HUCs that you have any knowledge of.

4. Navigate to the folder where you saved the files and open ClearwaterBasin.kmz.

– Google Earth will automatically open and ClearwaterBasin.kmz will appear in the toolbar on the left-hand side of the window, in the Places panel, under “Temporary Places”.

5. Right-click the ClearwaterBasin.kmz layer and choose “Save to My Places”.

–This will ensure this layer automatically loads every time you open Google Earth.

6. Click the arrow/plus sign to the left of the ClearwaterBasin.kmz layer until the list of HUCs appears below it.

7. Click the arrow/plus sign to the left of a HUC to drop down a list of PatchIDs in that HUC.

8. Navigate from patch to patch either by double clicking the patch numbers in the list (recommended) or by manually using your mouse.

– A patch is identified by connected streamlines of the same color.

9. Oftentimes it can be difficult to determine which stream (in reality) you’re looking at in Google Earth. Determine which streams constitute a patch by examining nearby streams, lakes, mountains, and man-made structures (e.g. roads, towns, etc).

– See Figure 2 for a recommended list of layers to activate (and deactivate) in order to display these landmarks. It is recommended that you turn off extraneous layers that add clutter without useful information.

10. When you have determined which stream(s) are in a patch, proceed to answer all questions from the Questionnaire pertaining to this patch. Record your answers in ClearwaterBasin_AnswerForm.xls.

– Some patches will have questions 1-2c blacked-out because these are the patches with known spawning or rearing Bull Trout.

11. After attributing each patch (i.e. answering possible questions) in a HUC, save ClearwaterBasin_AnswerForm.xls. Move on to a new HUC by selecting its worksheet in ClearwaterBasin_AnswerForm.xls and begin attributing its patches (see Step 7).

12. When finished with all the HUCs you have any knowledge of, email your completed ClearwaterBasin_AnswerForm.xls to Mike Heck.

Using Your Mouse to Navigate in Google Earth

1. To move across the landscape:

– Click, hold, and drag.

2. To zoom in:

– Scroll the mouse wheel up (away from you) a number of times.

3. To zoom out:

– Scroll the mouse wheel down (toward you) a number of times.

Note - If you zoom in far enough, your viewpoint tilts to a ground-level view. You can always reset the view to a top-down orientation by pressing the "u" key on your keyboard. You can also reset North to up by pressing the "n" key. Or, to reset to a top-down orientation AND set North to up, press the "r" key.

For more detailed instructions and tutorials, see Google Earth Help.

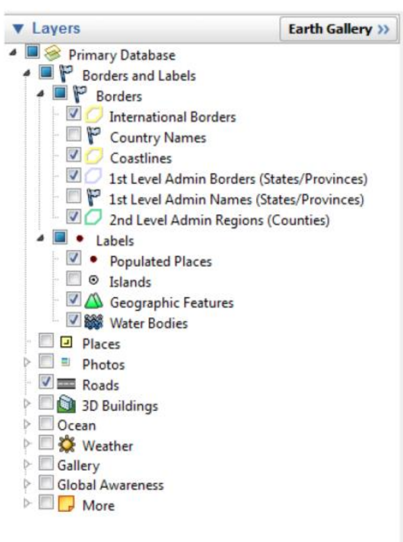
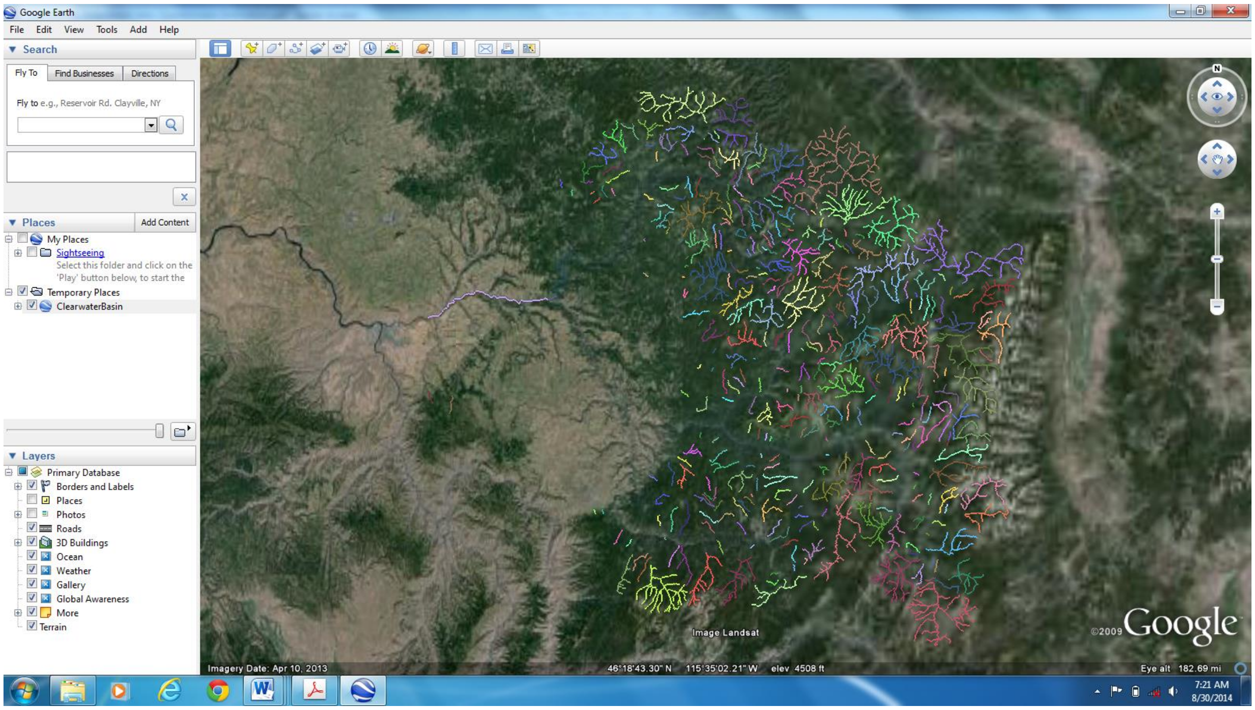


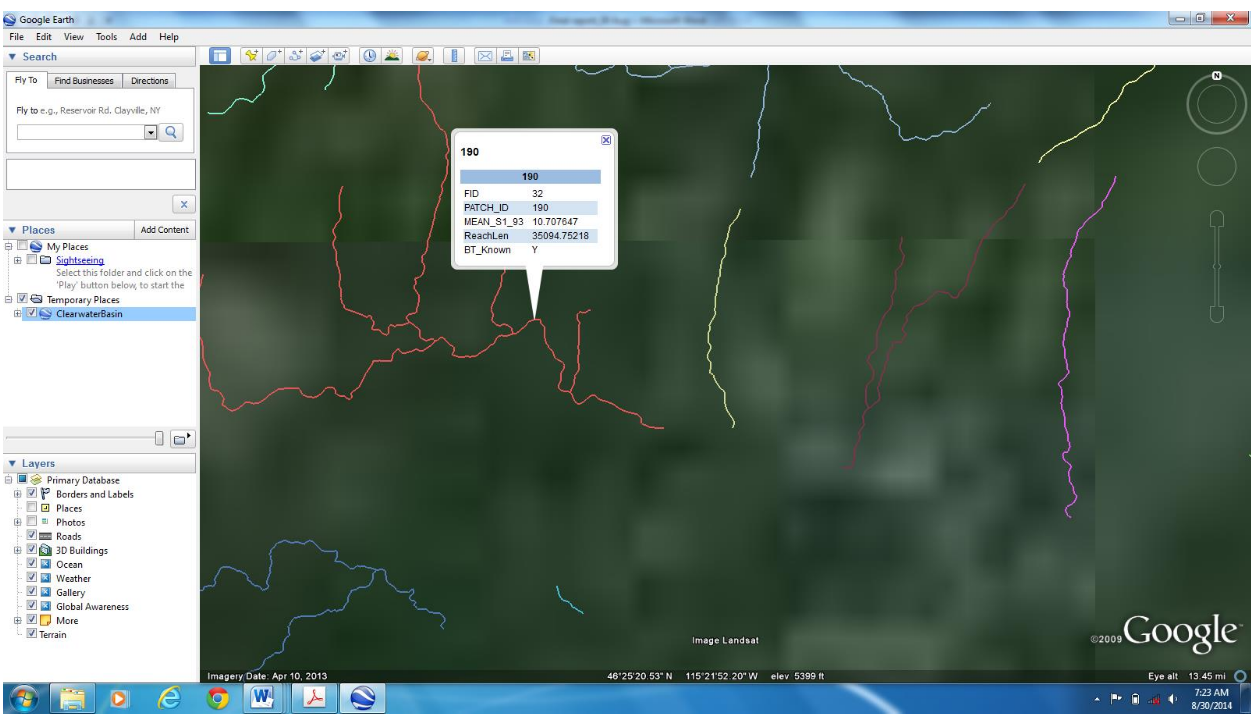
Figure 2. Screen capture from Google Earth of the Layers Panel with suggested layers to activate/deactivate.

A4. Illustration of Google Earth .kmz files used for patch attribution

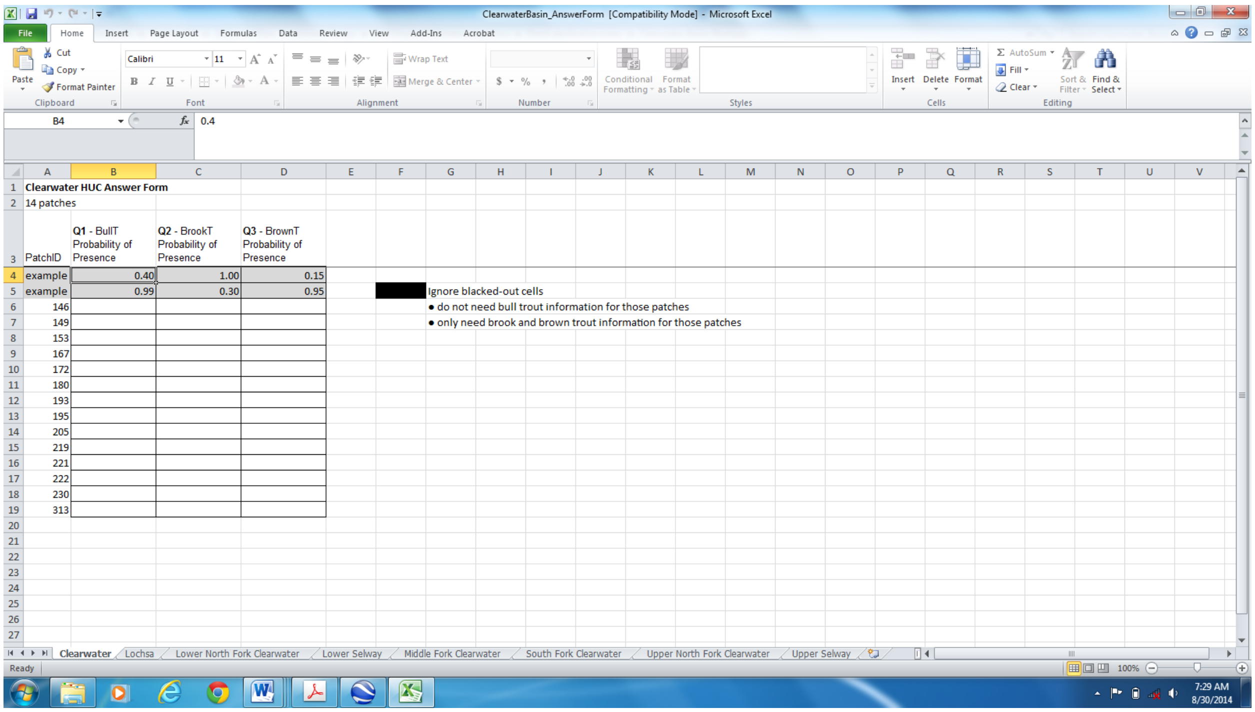
Screen capture of the Clearwater Basin, Idaho, showing patches (colored stream lines.



Example of attributes for a single patch within the Clearwater basin. Relevant attributes include a patch identifier (190) and presence of Bull Trout (BT_known, Y=yes, N=no).



Screen shot of excel file used in conjunction with printed map or Google Earth image for recording information on trout presence. Worksheet tabs correspond to 4th code HUCs within the Clearwater Basin.



A5. Notes from patch attribution in the Clearwater Basin provided by Katherine Thompson, Fisheries Program Manager, U.S. Forest Service, Clearwater-Nez Perce National Forest

Assumptions:

1. Brook Trout are detected everywhere they are present during snorkel, angling, or other observational surveys.
2. Brown Trout are not present in any stream or lake on the Nez Perce/Clearwater National Forests
3. Bull Trout may be present but are not always detected during snorkel and angling surveys, unless rigorous methods are used (electrofishing, night snorkeling, or repeated intensive day snorkeling in many reaches within a patch).
4. The probability that Bull Trout are present in a patch increases as stream order increases and stream gradient decreases

Rationale:

1. Bull Trout not present (0 probability):

    - Patch was in a very steep, 1st order tributary upstream of a known or suspected barrier
    - Past electrofishing surveys in multiple sites in patch did not find any Bull Trout
    - Repeated snorkel surveys in multiple sites within patch did not detect Bull Trout, and patch is upstream of a known barrier

2. Bull Trout present with low probabilities (0.1 – 0.4):

    - Patch was in a 1st order tributary to a known migration corridor with no known barrier, no survey data, and very small and steep stream (0.1 – 0.2)
    - Patch was in a 2nd order tributary to a known migration corridor with no known barrier, no survey data, and high stream gradient (0.2 – 0.3)
    - Patch was in a 3rd order or higher tributary to a known migration corridor with no known barrier, but past snorkel surveys in at least several sites within patch did not detect Bull Trout (0.2 – 0.4)

3. Bull Trout present with moderate to high probabilities (>0.4):

    - Patch was in a 3rd order or higher tributary flowing into known migration corridor, moderate to low stream gradient, no known barriers, no or limited survey data (0.4 – 0.6)
    - Patch was in a 3rd order or higher tributary with moderate to low stream gradient, no barriers to migration corridor, no or limited survey data, and within 0.25 miles or less to known occupied patch (0.7 – 0.8)
    -

4. Brook Trout present (1.0 probability)

    - Past snorkel, angling, or other observations in patch detected presence

5. Brook Trout not present (0 probability)

    - Past snorkel, angling, or electrofishing in patch did not detect presence
    - Patch was in a very steep, 1st order tributary upstream of a known or suspected barrier
    - Patch was in any order of stream, but in a watershed where Brook Trout have not been documented many surveys in many places in watershed, where stocking records do not indicate that Brook Trout were ever stocked, and where no mountain lakes in the watershed (if present) support Brook Trout.

6. Brook Trout present with low probabilities (0.1 – 0.3)

    - Patch in 1 – 2 order stream and no survey data in patch (0.1 – 0.3)
    - Patch was in a 3rd order or higher stream, no survey data in patch, no known barriers to migration corridor, but not adjacent to known Brook Trout population or downstream of a mountain lake with Brook Trout or stocking history (0.5 – 0.7)

7. Brook Trout present with moderate to high probabilities (0.4 – 0.9)

    - Patch was in a 3rd order or higher stream, no survey data in patch, no known barriers to migration corridor, high stream gradient, adjacent to known Brook Trout population, or downstream of a mountain lake with known Brook Trout or stocking history (0.5 – 0.7)
    - Patch was in a 3rd order or higher stream, no survey data in patch, no known barriers to migration corridor, moderate to low stream gradient, adjacent to known Brook Trout population, or downstream of a mountain lake with known Brook Trout or stocking history (0.8 – 0.9)

Notes: Q_1 indicated Bull Trout spawning and rearing, but current data from Forests suggest not:

<u>Lower Selway</u>
Patch 117 – high up in the Gedney watershed. Past surveys have not documented any Bull Trout. Additional sampling needed.

<u>South Fork Clearwater</u>
Patch 18 – Mill Creek. Has been surveyed (electrofishing and snorkel) multiple times in multiple places, only Bull Trout seen were 1 – 2 fluvial adults in lower reaches, suggesting FMO.
Patch 14 – in Crooked River headwaters downstream to Relief Creek, including Relief Creek. Although all of Crooked River is FMO, only upper reaches of West Fork and East Fork support spawning and rearing. Bull Trout not observed anywhere in Relief Creek. Patch is too big.
Patch 6 – Little Moose Creek, tributary to Red River. Bull Trout have not been observed in patch, additional surveys needed.
Patch 4 – Moose Butte Creek, tributary to Red River. Bull Trout have not been observed in patch, additional surveys needed.
Patch 35 – Red Horse Creek, tributary to Red River. Bull Trout have not been observed in patch, and patch is strongly occupied by Brook Trout. Additional surveys needed.

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